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EVIDENCE FOR RAPIDLY SPINNING BLACK HOLES IN QUASARS

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ABSTRACT

It has long been believed that accretion onto supermassive black holes powers quasars, but there has been relatively few observational constraints on the spins of the black holes. We address this problem by estimating the average radiative efficiencies of a large sample of quasars selected from the Sloan Digital Sky Survey, by combining their luminosity function and their black hole mass function. Over the redshift interval $0.4 < z < 2.1$, we find that quasars have average radiative efficiencies of $\sim 30\% - 35\%$, strongly suggesting that their black holes are rotating very fast, with specific angular momentum $a \approx 1$, which stays roughly constant with redshift. The average radiative efficiency could be reduced by a factor of $\sim$2, depending on the adopted zeropoint for the black hole mass scale. The inferred large spins and their lack of significant evolution are in agreement with the predictions of recent semi-analytical models of hierarchical galaxy formation if black holes gain most of their mass through accretion.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: nuclei — quasar: general

1. INTRODUCTION

Supermassive black holes are generally believed to be the power sources in quasars and other active galactic nuclei (Rees 1984), and in recent years there has been tremendous progress not only in measuring their masses but also in linking them to the global properties of their host galaxies (see reviews in Ho 2004). Apart from the mass, the other fundamental property of astrophysical black holes is the spin. However, to date there have been relatively few observational constraints. A handful of Seyfert galaxies, the most notable being MCG –6-30-15 (Wilms et al. 2001; Fabian et al. 2002), show a relativistically broadened, highly redshifted iron Kα line that can be most plausibly be interpreted as arising from a compact region around a rapidly rotating black black hole. The quasi-periodic variability detected in Sgr A*, both in the near-infrared and in the X-rays, can also be interpreted as evidence for a large spin for the Galactic Center black hole (Genzel et al. 2003; Ashenbach et al. 2004). Spectral fitting of the broad-band X-ray spectrum of active galaxies has achieved particular success by invoking ionized reflection disk models with inner disk radii sufficient compact to suggest maximally rotating black holes (Crummy et al. 2006). Lastly, mild evidence for rotating black holes has come from integral constraints derived for global populations of active galaxies. Yu & Tremaine (2002), applying Sołtan's (1982) argument to a sample of $z \approx 0-5$ quasars, concluded that their high average radiative efficiency ($\bar{\eta} \gtrsim 0.1$) implies that their black holes are spinning. Elvis et al. (2002) applied a similar calculation to the cosmic X-ray background and concluded that $\bar{\eta} \gtrsim 0.15$.

Theoretical considerations do not provide a clear prediction of the observational expectation. While gas accretion inevitably increases the spin of the black hole, as do mergers of comparable-mass black holes under most circumstances (Volonteri et al. 2005), minor mergers tend to have the opposite effect (Hughes & Blandford 2003; Gammie et al. 2004; Volonteri et al. 2005). Thus, the spin of the black hole of any given galaxy at any particular time depends on its specific merger history up to that point.

In this Letter, we attempt to constrain the spins of supermassive black holes by estimating the average radiative efficiency of a large sample of quasars with redshifts $z = 0.4-2.1$. The underlying assumption of our method is that black holes attain most of their mass through accretion. We find that quasars radiate with a high efficiency ($\bar{\eta} \approx 0.3-0.35$), from which we infer that their black holes are rapidly rotating. Throughout, our calculations assume the following cosmological parameters: $H_0 = 70$ Mpc^{-1} km s^{-1}, $\Omega_{\rm M} = 0.3$, and $\Omega_\Lambda = 0.7$.

2. ACCRETION-GROWTH EQUATION AND RADIATIVE EFFICIENCY

If quasar light derives from accretion of matter onto a black hole, then the radiative efficiency is $\eta \approx \Delta\epsilon/\Delta\rho_\bullet c^2$, where the black hole mass density increase $\Delta\rho_\bullet$ in a redshift interval Δz at z results in an increase of the radiative energy density $\Delta\epsilon$. In practice, $\Delta\epsilon$ can be derived from the quasar luminosity function and $\Delta\rho_\bullet$ can be obtained from the mass distribution function. Thus, we can estimate the radiative efficiency at any redshift, and hence place a strong constraint on the average spin of black holes, since η varies as a function of spin (~ 0.06 and 0.42 for a non-rotating and a maximally rotating black hole, respectively). If black hole masses are known for a quasar sample, we can define their mass distribution function as

$$\Phi(M_\bullet, z) = \frac{{\rm d}^2N}{{\rm d}M_\bullet {\rm d}V}, \tag{1}$$

where $M_\bullet$ is the black hole mass, dN is the number of quasars within the comoving volume element dV and mass interval d$M_\bullet$. Then the integrated mass density of black holes with $M_\bullet \geq M_\bullet^{\rm c}$ at a redshift z is given by

$$\rho_\bullet(z) = \int_z^\infty {\rm d}z \int_{M_\bullet^{\rm c}}^\infty M_\bullet \Phi(M_\bullet, z){\rm d}M_\bullet, \tag{2}$$

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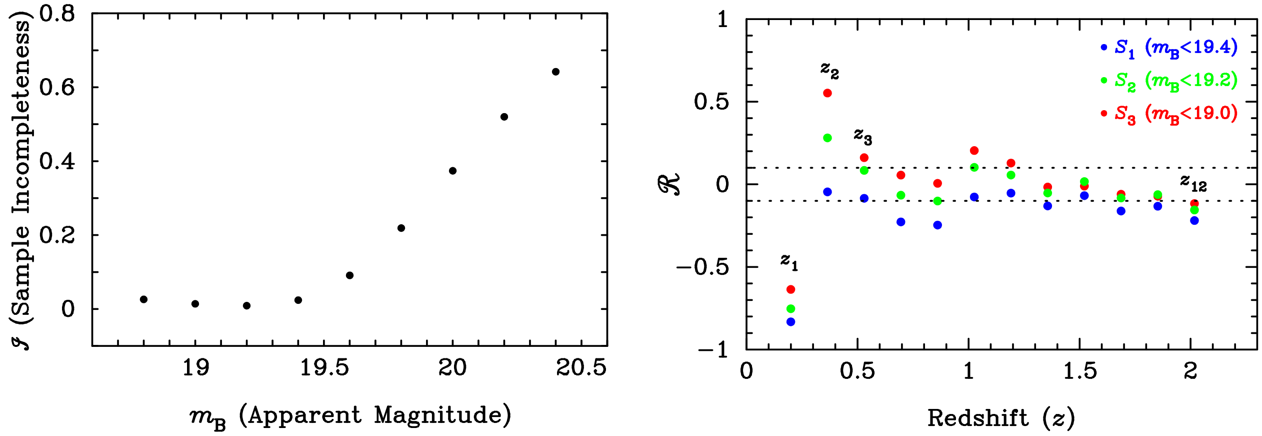

FIG. 1.— (*Left*) The global incompleteness of the sample as a function of apparent magnitude. Note that the sample becomes increasingly incomplete for $m_B \gtrsim 19.5-19.6$ mag. (*Right*) Test of the completeness of each of the three samples, for different redshift bins. The bins z_1 and z_2 poorly match the SDSS quasar luminosity function of Richards et al. (2006). This can be attributed to the inhomogeneity of the McLure & Dunlop (2004) sample in the redshift interval $z = 0.117-0.4$; these two bins are excluded from the analysis. The other redshift bins have a completeness level of at least 98%.

where $M_\bullet^c$ is a lower limit set by the flux limit of the survey.

Accretion of matter onto a black hole generates radiation and increases the mass of the hole. The relationship between the radiated energy and the accumulated mass density in black holes can be expressed by the accretion-growth equation as

$$\rho_\bullet(z) = \int_z^\infty \frac{\mathrm{d}t}{\mathrm{d}z}\mathrm{d}z \int_{L_{\rm min}(z)}^\infty \frac{(1-\eta)}{\eta}\frac{L_{\rm bol}}{c^2}\Psi(L,z)\mathrm{d}L, \quad (3)$$

where $L_{\rm min}(z)$ is the minimum luminosity of the survey at redshift z, c is the speed of light, $L_{\rm bol}$ is the bolometric luminosity, $\Psi(L,z)$ is the luminosity function of the quasar sample, L is the specific luminosity, and the radiative efficiency η varies with redshift. Equation (3) involves a relation between the bolometric and specific luminosities. We convert the B-band luminosity L_B into the bolometric luminosity via $L_{\rm bol} = C_B L_B$, where $C_B \approx 6-7$ is the B-band bolometric correction factor for quasars brighter than $L_{\rm bol} \approx 10^{11.5} L_\odot$ (Marconi et al. 2004); we adopt $C_B = 6.5$. Since the spectral energy distributions of quasars show little evidence for redshift evolution (Shemmer et al. 2005; Strateva et al. 2005; Steffen et al. 2006), we assume that C_B does not vary with redshift. With $\Phi(M_\bullet,z)$ and $\Psi(L,z)$, the average radiative efficiency $\bar{\eta}(z)$ at each redshift bin follows from the differential version of Equation (3):

$$\bar{\eta}(z) = \frac{\Delta\epsilon}{\Delta\epsilon + \Delta\rho_\bullet c^2}, \quad (4)$$

where

$$\Delta\epsilon = \Delta z\,\frac{\mathrm{d}t}{\mathrm{d}z}\int_{L_{\rm min}(z)}^\infty L_{\rm bol}\Psi(L,z)\mathrm{d}L \quad (5)$$

and

$$\Delta\rho_\bullet = \Delta z\int_{M_\bullet^c}^\infty M_\bullet\Phi(M_\bullet,z)\mathrm{d}M_\bullet. \quad (6)$$

Assuming that the innermost stable circular orbit is the inner radius of the accretion disk (Bardeen et al. 1972), the inferred radiative efficiency yields an estimate of the black hole spin.

Equation (4) constrains the radiative efficiency at *any* redshift, provided the black hole mass function is known. It should be stressed that both sides of Equation (3) only include the actively black holes (i.e. quasars), and thus the radiative efficiency from Equation (4) does not rely on the lifetime of quasars. This method is also independent of obscured sources, which is an important complicating factor in estimation of the radiative efficiency using Sołtan's method (Elvis et al. 2002; Yu & Tremaine 2002).

3. APPLICATION TO SDSS QUASARS

3.1. *Estimation of black hole masses*

The large database provided by the Sloan Digital Sky Survey (SDSS; York et al. 2000) affords us an excellent opportunity to examine this problem. Reverberation mapping of local active galaxies has resulted in empirical scaling relations based on quasar luminosity and broad emission line width (Kaspi et al. 2000; McLure & Jarvis 2002; Vestergaard 2002) that enable "virial" black hole masses to be obtained, and hence the distribution function for the black hole masses of a sample of quasars can be estimated independently from their luminosity function. Because the profile of the C IV line is complex and may be strongly affected by outflows (Baskin & Laor 2005), we only consider objects with broad Hβ and Mg II lines detected in SDSS. This limits the maximum redshift of the present sample to $z \leq 2.1$. For quasars with $z \leq 0.7$, we obtain the virial black hole masses using the FWHM of the Hβ line ($V_{\rm H\beta}$) following the empirical relation[5]

$$M_\bullet = 4.7\times10^6\left(\frac{L_{5100}}{10^{37}\rm W}\right)^{0.61}\left(\frac{V_{\rm H\beta}}{10^3\ \rm km\ s^{-1}}\right)^2 M_\odot, \quad (7)$$

where L_{5100} is the specific continuum luminosity at 5100 Å. For higher redshift quasars ($0.7 < z \leq 2.1$), we use the FWHM of Mg II ($V_{\rm Mg\,II}$) to estimate the black hole mass, using the calibration (McLure & Dunlop 2004)

$$M_\bullet = 3.2\times10^6\left(\frac{L_{3000}}{10^{37}\rm W}\right)^{0.62}\left(\frac{V_{\rm Mg\,II}}{10^3\ \rm km\ s^{-1}}\right)^2 M_\odot, \quad (8)$$

where L_{3000} is the specific continuum luminosity at 3000 Å. The scatter of these relations has been estimated to be ∼0.4 dex (McLure & Dunlop 2004).

[5] This relation for Hβ is based on the original work of Kaspi et al. (2000), which has since been recalibrated (Onken et al. 2004; Kaspi et al. 2005). The new calibration increases the zeropoint of the mass scale by roughly a factor of 2. However, the new zeropoint has not been established with great statistical certainty (Nelson et al. 2004; Greene & Ho 2006), and for the current application we will retain the original zeropoint of Kaspi et al. (2000), on which the masses derived by McLure & Dunlop (2004) are based.

3.2. *Samples*

Our analysis is based on black hole masses calculated by McLure & Dunlop (2004) for 12,698 quasars in the redshift range $0.1 \leq z \leq 2.1$, for which good-quality spectra are available from the quasar catalog of the First Data Release (DR1) of SDSS (Schneider et al. 2003). This sample, however, is neither complete nor homogeneous. To evaluate its completeness, we compare it to the quasar luminosity function recently determined for the Third Data Release (DR3) of SDSS (Richards et al. 2006). After dividing the sample into $n_z = 12$ redshift bins, we evaluate the two parameters

$$\mathcal{R}_i = \frac{N^i_{\rm bin} - N^i_{\rm LF}}{N^i_{\rm LF}}; \qquad \mathcal{I} = \sum_{i=1}^{n_z} \mathcal{R}_i^2, \tag{9}$$

where $N^i_{\rm bin}$ is the number of quasars within the redshift bin z_i and $z_i + \Delta z$ and $N^i_{\rm LF}$ is the number of quasars calculated from the luminosity function. The parameter $\mathcal{R}_i$ measures the degree of incompleteness of the sample at each redshift bin z_i, and $\mathcal{I}$ indicates the global incompleteness of the sample. By adjusting the apparent magnitude m_B, we can define subsamples with different levels of completeness. As illustrated in Figure 1 (*left*), the sample incompleteness begins to be noticeable for $m_{\rm B} \gtrsim 19.5$–19.6 mag. Furthermore, Figure 1 (*right*) shows that the number of quasars in the first two redshift bins matches poorly with the predictions based on the luminosity function of Richards et al. (2006). We thus restrict our attention to the redshift range $0.4 \leq z \leq 2.1$, and consider only three subsamples, S_1, S_2 and S_3, which correspond to apparent magnitude limits $m_{\rm B} < 19.4$, 19.2, and 19.0 mag, respectively. The completeness level of these subsamples is $\gtrsim 98\%$.

3.3. *Results*

We show the differential black hole mass density ($d\rho_\bullet/dz$) as a function of redshift in Figure 2*a*. We find that the black hole density is very sensitive to the limit magnitudes of the samples. The quasar luminosity function from SDSS DR3, as given by Richards et al. (2006), is

$$\Psi = \Psi_* 10^{A_1\left[M_i - (M_i^* + B_1\xi + B_2\xi^2 + B_3\xi^3)\right]}, \tag{10}$$

where M_i is i–band magnitude, $\xi = \log\left[(1+z)/(1+z_{\rm ref})\right]$, $A_1 = 0.84$, $B_1 = 1.43$, $B_2 = 36.63$, $B_3 = 34.39$, $M_i = -26$, $z_{\rm ref} = 2.45$ and $\Psi_* = 10^{-5.7}$. Inserting the luminosity function and the mass distribution function into Eq. (4), we immediately arrive at the radiative efficiency plotted in Figure 2*b*. Independent of the chosen subsample, we find that quasars radiate at a high efficiency, with $\eta \approx 0.3 - 0.35$, roughly independent on redshift from $z \approx 0.4$ to $z \approx 2$. The average radiative efficiency we obtain is significantly higher than that corresponding to the maximum spin ($a \approx 0.9$) achieved by a magnetohydrodynamic thick disk (Gammie et al. 2004), $\eta \approx 0.2$, but is consistent with the efficiency of Thorne's (1974) limit of $a = 0.998$ ($\eta = 0.32$), as well as that of extreme Kerr rotation $a = 1$ ($\eta = 0.42$). A similar conclusion has been reached by other studies, based on models of hierarchical galaxy formation (Volonteri et al. 2005) and considerations of the cosmic X-ray background radiation (Elvis et al. 2002). We should note that Elvis et al. (2002) only gave a lower limit on the efficiency ($\eta > 0.15$), and no detailed information at any given redshift. The observed high value and constancy of η suggests the spin angular momentum of most or all black holes in quasars have saturated at their maximum value and undergo no evolution from $z \approx 2$ to $z \approx 0.4$. Our results are consistent with the conclusions of Volonteri et al. (2005).

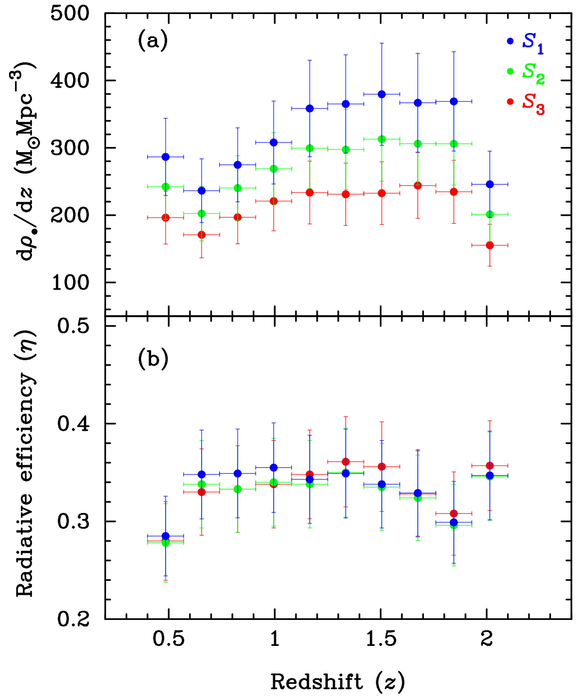

FIG. 2.— The black hole mass density (*a*) and the radiative efficiency (*b*) as a function of redshift for three quasar samples (S_1, S_2 and S_3) from the SDSS DR1. The error bars on $d\rho_\bullet/dz$ and η are dominated by the uncertainty in the black hole masses.

4. DISCUSSION AND SUMMARY

We have estimated the average radiative efficiency, and hence the spin, of supermassive black holes by combining the luminosity and black hole mass function of a large sample of SDSS quasars selected over the redshift interval $0.4 < z < 2.1$. With find that the average radiative efficiency is very high, $\bar{\eta} \approx 0.3 - 0.35$, which implies that the black holes are rotating very fast, with $a \approx 1$. No noticeable evolution is seen over this range of redshifts; it would be very interesting to extend this study to higher redshifts ($\gtrsim 2$) in order to establish the epoch over which the black hole spins were imprinted. We note that our conclusions are only based on the accretion-growth equation, which makes no reference to whether the black mass was gained principally through accretion or mergers. An advantage of the present approach is that the result does not depend on the lifetime of quasars.

The large spins deduced for the black holes in quasars may arise quite naturally as a consequence of major (nearly equal-mass) galaxy mergers. Massive, gas-rich mergers account not only for most of the star formation in the Universe at $z \approx 2 - 3$ (e.g., Conselice et al. 2003), but they are probably also responsible for triggering major episodes of quasar activity (Di Matteo et al. 2005). When galaxies merge, so, too, do their black holes (if they exist in the parent galaxies), at least in principle. The spin angular momentum of black holes newly born from mergers is expected to be high, with $a > 0.8$, its exact value depending on the orbit of the original binary (Gammie et al. 2004). Subsequent accretion at an Eddington-limited rate will further increase the spin on a timescale shorter than the Salpeter time ($\tau = 0.45$ Gyr) (Volonteri et al. 2005). The newborn holes can thus rapidly evolve into Kerr holes, consistent with our results.

The high radiative efficiency prolongs the lifetime of a quasar's accretion. Following Shapiro (2005), the mass of an

accreting black hole at time t with an initial mass M_0 is given by

$$M_\bullet(t) = M_0 \exp\left[\frac{\dot{m}(1-\eta)}{\eta}\frac{t}{\tau}\right], \qquad (11)$$

where $\dot{m} = \dot{M}_{\rm acc}c^2/L_{\rm Edd}$, $\dot{M}_{\rm acc}$ is the accretion rate, and $L_{\rm Edd}$ is the Eddington luminosity. The anticipated lifetime of an e–fold accretion-growth is then $t_{\rm QSO} \approx \eta\tau/\dot{m}(1-\eta) \approx (0.4-0.7)\tau \approx 0.2-0.3$ Gyr for $\eta = 0.3-0.4$ if the hole is accreting at the Eddington rate ($L_{\rm Edd}/c^2$). This lifetime lies within the range of values currently estimated for quasars (Martini 2004), but is uncomfortably long for the highest-redshift quasars known ($z \gtrsim 6.4$), whose large masses ($M_\bullet \approx 10^9 M_\odot$), if grown from much smaller seeds, would have required much more rapid growth rates (Shapiro 2005).

One major caveat affects the actual numerical value of $\bar{\eta}$. We noted in §3.1 that our black hole mass scale is based on the original zeropoint of Kaspi et al. (2000), whose accuracy is currently still a subject of debate. If the zeropoint in fact should be increased by a factor of $\sim$2, as suggested by some recent studies, then the radiative efficiency would *decrease* by the same factor, to $\bar{\eta} \approx 0.2$. This lower value of $\bar{\eta}$ would help alleviate the conflict with the growth rate of the highest-redshift quasars (Shapiro 2005), would be consistent with the theoretical expectation of magnetohydrodynamic thick disks (Gammie et al. 2004), and would bring it in better agreement with the independent estimates of radiative efficiencies derived from Sołtan-type arguments. The analysis of optically selected quasars by Yu & Tremaine (2002) obtains $\bar{\eta} \gtrsim 0.1$ assuming a bolometric correction of $C_B = 11.8$. If $C_B = 6.5$ had been adopted, as suggested by Marconi et al. (2004), Yu & Tremaine's value of $\bar{\eta}$ would be lower by a factor of ~ 2. On the other hand, this type of estimate is seriously affected by uncertainties in the contribution from obscured active galaxies, which is currently poorly known (Martinez-Sansigre et al. 2005). Estimates of the average radiative efficiency using an energy density based on the cosmic X-ray background, which is less affected by obscuration, yield values of $\bar{\eta}$ ($\gtrsim 0.15$; Elvis et al. 2002) that are more consistent with our results.

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